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ECL 183

THE DEVELOPMENT OF A CAST MONOFORM TURBINE WHEEL

When the AiResearch Manufacturing Company of Arizona began to experience widespread premature failure of the two-piece turbine wheel in one of their radial inflow gas turbine engines, it was decided to develop a cast monoform (one piece) wheel of advanced aerodynamic shape to replace the two-piece assembly in existing as well as future production units. This was accomplished using advanced casting techniques.

 Written by Capt. R. B. McCollough and published with financial support from the National Science Foundation. Permission to print granted by The AiResearch Manufacturing Company.

I. INTRODUCTION AND OVER VIEW

The AiResearch Manufacturing Company of Arizona has produced approximately 80 percent of the small gas turbine engines in use in the world. Since 1953, the GTCP-85 series of engines has been a mainstay of the AiResearch line. It is used primarily for aircraft auxiliary power units and for ground power generators for aircraft. The engine is a single shaft, two bearing, gas turbine engine with a two stage centrifugal compressor and a single stage radial inward flow turbine. The various models of the GTCP-85 weigh between 275 and 300 pounds and produce between 200 and 350 horsepower. This power is normally utilized in varying combinations of shaft power and compressed air. Some of the more than twenty types of aircraft which use this engine are the Lockheed C-141, the Douglas DC-9, and the Boeing 727.[4]

Despite an enviable service record, it became apparent in the mid-1960's that the redesign of the turbine wheel of the GTCP-85 series was imperative. Continuous engineering improvements to all parts of the engine since its earliest production had succeeded in greatly improving its performance reliability; however,

the increasing power requirements of the aircraft system which it was called upon to support brought about a point of diminishing returns past which a major design improvement was necessary in order to maintain a satisfactory level of reliability. The turbine wheel assembly was pinpointed as the most lucrative area for major improvement efforts since more than one-half of all premature engine failures were occurring there.[6]

Specifically, with the introduction into service in 1967 of the Boeing 727-200 series aircraft, which uses the GTCP-85-98C for auxiliary power, rapid failure of the two-piece turbine wheel assembly became prevalent. Examination of these engines after 1900 hours of operation frequently revealed sufficient damage to the turbine wheel assembly to justify replacement under the 2000 hour warranty. The cause of this damage was determined to be the extended operation of the engines at excessive turbine inlet temperature (TIT). These excessive TIT's were, in turn, made necessary by the need to operate the engine at the upper limits of its power potential in order to obtain the power required by the 727-200 system.

After analysis of the problem, it was decided in early 1968 to develop a cast, monoform, 20 blade

turbine wheel of advanced aerodynamic shape to replace the two-piece turbine assembly which had been used in this engine since its inception. In the interim, customer airlines were requested to reduce the operating TIT in their APU's by 100° in order to extend the useful life of their present units until a retro-fit package containing the new wheel could be made available. It was pointed out that this TIT reduction would result in only a 2-1/2° increase in the aircraft cabin temperature, the aircraft air conditioning pack being powered by the APU.

Several points were considered in deciding to modify the GTCP-85 rather than to substitute another engine of greater capacity.

1. Of the two other engines of similar capacity in the AiResearch inventory, one did not have the bleed air capability necessary to replace the '85, and the other was developed exclusively for the Air Force C-5A air craft.

2. Naturally, the development of a completely new engine would have been vastly more expensive than modifying the existing one.

3. The GTCP-85 having been in widespread use for many years was well known throughout the world, and service and parts were easily available to all users.

4. It was felt that the improved wheel, easily substituted for the old two-piece assembly, would be attractive as a retro-fit item to all owners of the earlier models.

Having designed the monoform wheel, three foundries were selected as potential sources of manufacture, and were commissioned to produce test lots of the new wheel. One of the foundries was eliminated as a source due to their reluctance to modify their casting procedures in order to prevent a defect which appeared in one of their early castings.

In 1962, a cast monoform wheel had been attempted. This wheel, cast in the same shape as the two-piece wheel, was abandoned when it experienced a hub burst after ten hours of testing.

In 1966, another engine, the GTCP-36, had been developed, and this engine incorporated a cast monoform turbine wheel of advanced design. From this it was known, in 1967, when the failure rate of the GTCP-85 became unacceptably high, that the technology was available at last to produce a cast monoform wheel for the '85.

In December of 1969, the monoform wheel was made available to the airlines and was incorporated into the production of the GTCP-85. As a result of aerodynamic and metallurgical improvements, increased efficiencies and lower operating temperatures, along with the desired increase in performance reliabilities, were obtained. The monoform wheel delivers an efficiency of about 80%, as opposed to the 75% of the two-piece wheel. Since the rated output of the engine remained the same, this increased efficiency resulted in a decrease of 30 pounds per hour in full-load fuel consumption rate, and in a 100°F lower operating temperature.

Chronology of Events

1953	GTCP-85 first produced, two-piece wheel used.
1962	One-piece cast wheel attempted.
1966	GTCP-36 engine developed using cast monoform wheel.
1967	Boeing 727-200 series aircraft introduced. GTCP-85-98C exhibits high premature failure rate.
1968	Expedited development of monoform wheel for GTCP-85 begins.
1969	January - first castings attempted at AiResearch Casting Division April - successful castings first produced. December - new wheels delivered to the airlines.

II. TURBINE WHEEL DEVELOPMENT

II.1 The Two-piece Wheel Assembly

Since the inception of the engine, the turbine wheel of the GTCP-85 had been manufactured in two parts. The lower section, with straight blades, was forged and machined of Waspalloy. The upper section, or exducer, with sharply curving blades, was cast of Inconel 713C. The wheel had twelve blades and was sectioned at a point just before the curve of the blades became sharply pronounced (see Figure 2.1). The two pieces were joined by means of a pressed ring joint. This design delivered good efficiency and reliability for many years until increasing demands upon the engine required its operation at high turbine inlet temperatures (TIT), which caused rapid metallurgical deterioration.

Temperature is an important parameter in the service life of any metal device, and especially in turbine section components, which are exposed to extremely high temperatures. The time-to-failure of a turbine component varies inversely with its operating temperature. A decrease of as much as 50% in the service life of a turbine section component may be caused by an increase

of as little as 25°, in the 1500° to 1700° range typical of gas turbine engines.

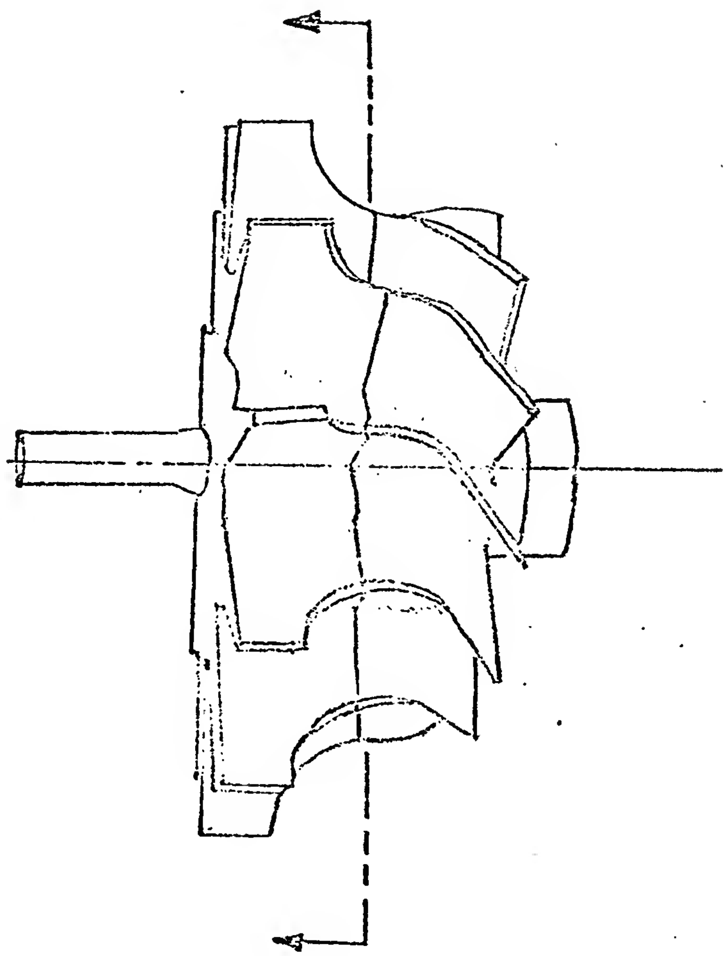

Fig. 2.1 Two-Piece Turbine Wheel Assembly

A typical Temperature vs. Fatigue Strength curve may be seen in Figure 2.2. Fatigue strength is defined as the level of stress at which a metal can be expected to survive 10^6 cycles.

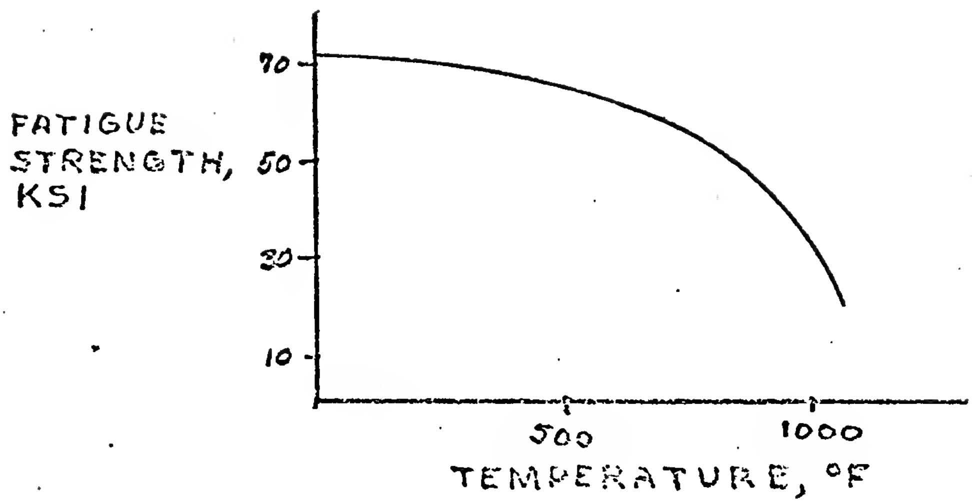

Fig. 2.2 Fatigue Strength vs. Temperature for 4340 Chrome-Moly Steel

The necessity to operate the engines at high TIT may be explained by reference to a Temperature vs. Entropy diagram (see Figure 2.3). The process shown is an idealized Brayton Cycle, the pattern cycle common to gas turbine engines. The process 1-2 represents compression; 2-3, heat addition due to fuel combustion; and 3-4-5, expansion across the turbine. The work done by the engine is represented by the length of the line 3-4-5. The distance 3-4 is equal to 1-2, and represents the work necessary to power the compressor. The distance 4-5 represents the net work done by the engine. Since power is defined as the time rate of doing work, this may also

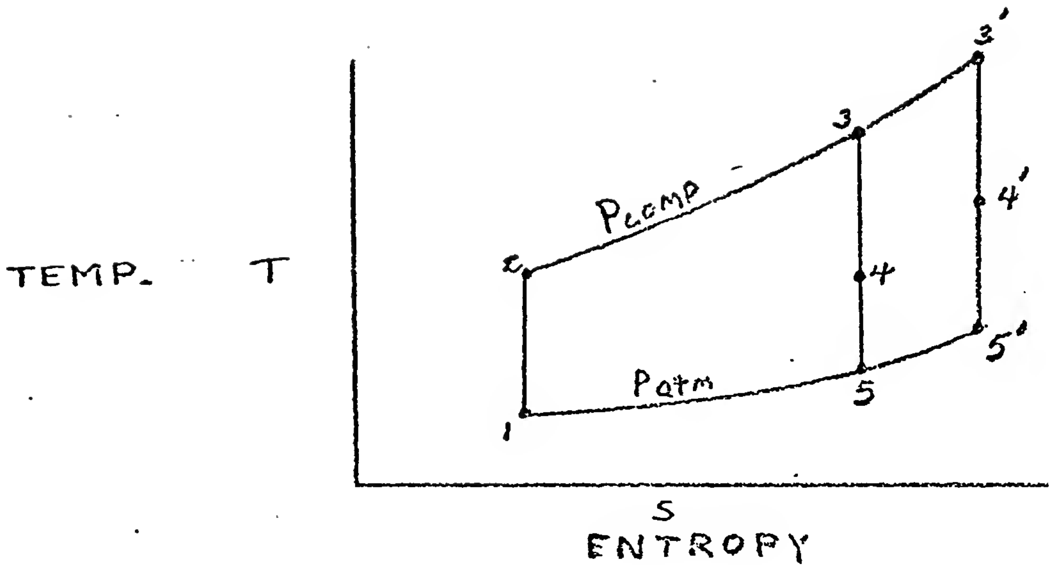

Fig. 2.3 Brayton Cycle

be considered a measure of the power available from the engine. If the TIT alone is increased, (process 3-3') then the line 3'-4'-5' represents the work done at the new inlet temperature. Compressor work remains unchanged, so 3'-4' is equal to 3-4 and 1-2; and, since lines of constant pressure diverge on the T-S plot as entropy increases, 4'-5' is greater than 4-5. Hence, an increase in TIT will yield an increase in work if all other factors remain unchanged. In the case of a given engine, the atmospheric pressure, Patm, remains constant. Since the combustor pressure, P_c, is limited by the allowable RPM limit of the engine, it may therefore be considered

constant. From this, it becomes obvious that in order to increase the work done within any given time (power), it is necessary to increase the TIT, which is the only variable parameter available, once the maximum engine speed is reached.

II.2 The Monoform Wheel

Since the earliest days of the GTCP-85, AiResearch engineers realized that the most desirable design for the turbine wheel was a cast monoform configuration. There are numerous advantages inherent in such a design. First, it is possible to achieve a more aerodynamically perfect shape by casting than by any other process. Secondly, the one-piece design eliminates the need for any joining device between the upper and lower halves of the wheel. This joint, in addition to requiring extra machining, and therefore extra cost, was also a source of imbalance and vibration. Next, the one-piece configuration eliminates the break in the surface between the wheel halves, a source of aerodynamic losses. Additionally, manufacturing and replacement cost are lowered by the one-piece cast design due to the fact that the casting costs are less than machining costs for complex shapes, and the number of parts to be manufactured and handled is reduced. Until the late 1960's, however, the

practical production of such a wheel was beyond the technical abilities of the commercial foundries. Therefore, a two-piece wheel assembly was used as a compromise between the desirable and the practicable.

The comparative configurations of the two wheels are shown in Figures 2.1, 2.4, and 2.5. The twenty blade

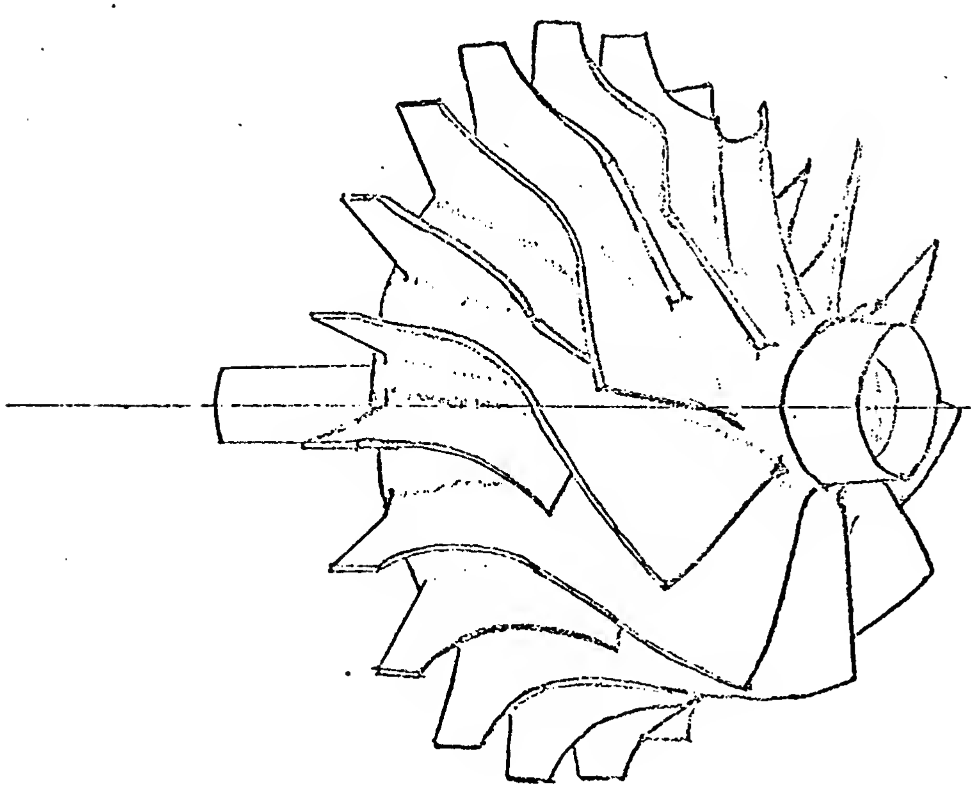

Fig. 2.4 Monoform Turbine Wheel

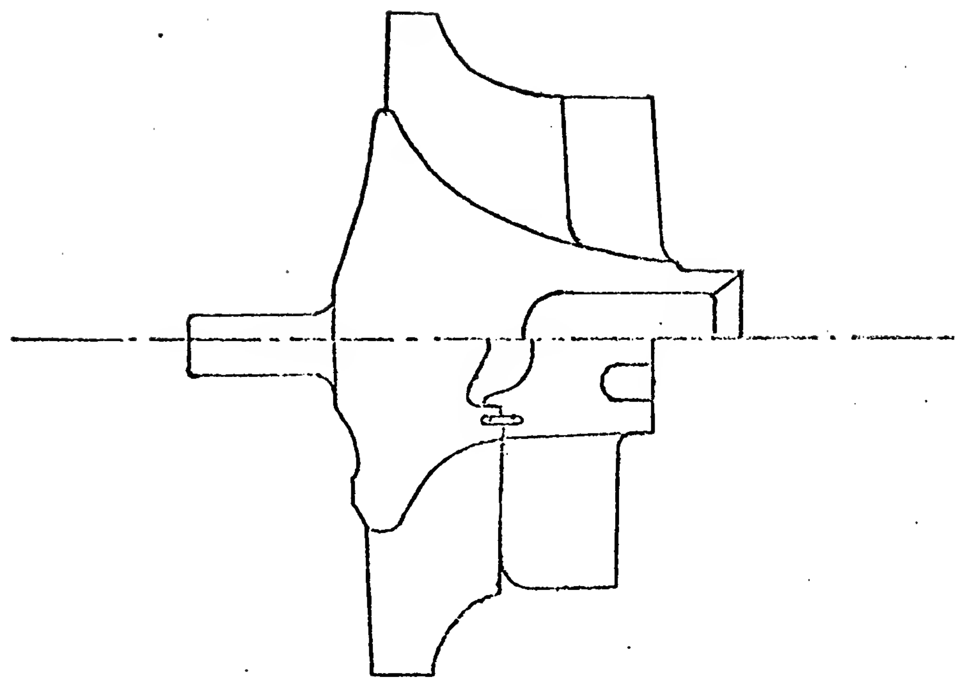

Fig. 2.5 Comparative Cross Sections

design for the new wheel was chosen because, generally speaking, the efficiency of a turbine wheel increases as the number of blades is increased. This is true because as the gases flow between two blades, a certain amount of the gas is able to flow through the center of the channel without losing much of its kinetic energy. Also, a wide channel encourages losses due to secondary flow and turbulence. Additional blades narrow this channel and help to prevent these losses, although, naturally, a point is eventually reached at which increased skin friction offsets these benefits. This accounts for the

fact that every other blade on the monoform wheel is a "splitter" blade which runs only half the axial length of the wheel. These blades serve to guide and extract extra energy from the gases near the inlet where the large hub diameter allows large channels between the full-length blades. The splitter blades terminate approximately halfway down the hub because the rapidly decreasing hub diameter narrows the channel to the point where the additional blade surface would cause high losses due to skin friction.

Another source of losses in the two-piece design is the abruptness of the change in direction to which the gases are subjected as they follow the shape of the hub. The view of comparative cross sections in Figure 2.5 illustrates the less abrupt, therefore more efficient, taper in the monoform hub. A similar gain is achieved by the smoother and more gradual twist of the blades of the monoform wheel as they change direction from axial at the inlet edge to nearly radial at the exhaust edge. On the two-piece wheel, the blades run straight axially on the lower half, then curve abruptly on the exducer.

The advanced shape of the monoform wheel is made possible by casting. It would be prohibitively expensive to produce such a wheel by any combination of other metal

shaping processes. The monoform wheel is produced for approximately $1,500, while it has been estimated that the same wheel would cost $8,000 if machined.

II.3 Stress Analysis

A complete stress analysis of the monoform wheel was performed by the engineers at AiResearch. Their primary tool in this analysis was the Finite Element Grid Method. This technique involves the use of a computer program which relates the various parameters of stress, load, rotational speed, time, temperature propagation, material stiffness, etc., in order to calculate internal stress at any point in the wheel at any given time. An approximate picture of the stress distribution of the wheel is shown in Figure 2.6.

It has been established that the most likely locations for cracks to develop are at the shoulders of the blades, where the edges of the blades join the hub of the wheel. These points are subject to compression stresses during start-up and to tensile stresses during cool-off. This is due to the fact that the thin blades heat up and cool off much more quickly than the hub. Around the base of the hub, hoop compression is experienced due to the impingement upon this area of the hot gases from the nozzle. These thermal stresses are made

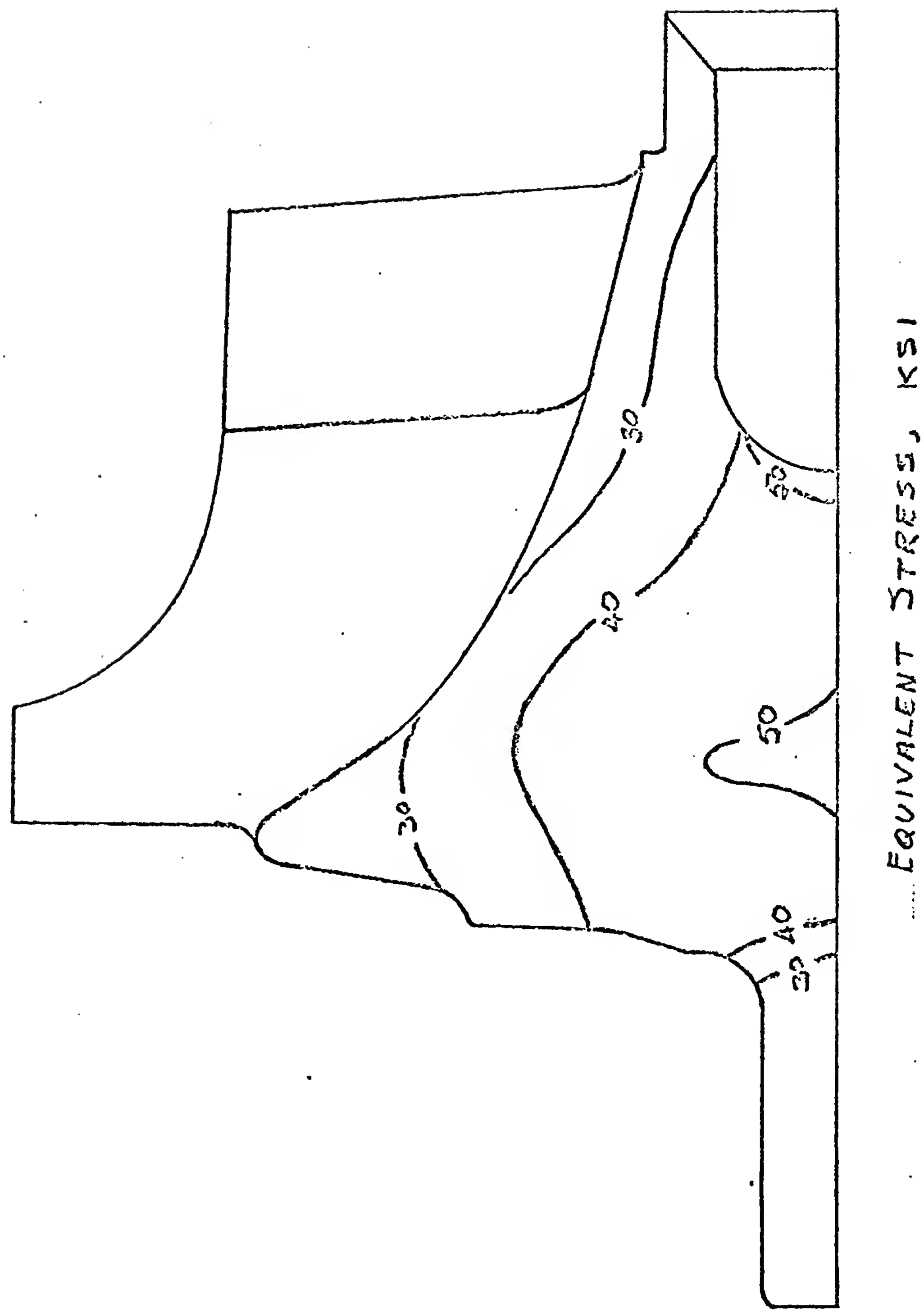

Fig. 2.6 Equivalent Stress Distribution

more severe than would normally be supposed by the low ambient temperatures to which the APU engine is exposed at flight altitudes. Early cracks are frequently observed after as few as 1,000 start-stop cycles. Extensive testing of compact fracture specimens cut from actual castings has enabled AiResearch engineers to closely predict, according to size and location, the effect of any crack upon the life of the turbine wheel.

III. PRODUCTION OF THE MONOFORM WHEEL

III.1 The Casting Process

Ultimately, the key to the entire engineering process was the casting process. Deficiencies in the state of the art of metal casting were the primary reason why a one-piece wheel had not been previously produced. By now, 1968, it had been demonstrated by the production of a cast monoform wheel for the GTCP-36 engine that the techniques were now available to produce a similar wheel for the GTCP-85. AiResearch, determining that it was desirable to have at least two sources of supply for the new wheels, sent a master wax injection tool to five foundries including their sister organization, AiResearch Casting Division (ACD), in Torrance, California, for the purpose of producing samples of the wheel for acceptance testing. The material to be used was INCO 713 LC. Of these five foundries, three were originally commissioned to produce the monoform wheel. One of these was eliminated later after one of their castings experienced a hub burst during acceptance testing. This particular foundry was unwilling to comply with procedural changes which AiResearch engineers felt were indicated by their investigation into the causes of

the failure. This failure and its investigation will be discussed in greater detail later.

The process used to cast the monoform wheel involves the production of an individual mold for each wheel. The master wax injection tool produces a wax pattern of the exact dimensions of the turbine wheel, allowing for minimal finish machining. The pattern is coated with successive layers of ceramic "stucco" material. After the stucco has hardened, it is heated to melt the wax, which is then poured out, leaving a perfect ceramic mold for the metal pour. Following the removal of the wax, the mold is coated with additional insulating material which aids in the precise regulation of the rate at which the casting cools.

The cooling rate of different parts of the mold may be varied by adding more or less of the insulating material. When the mold has cured, the metal pour is made. The "Hot Top" technique is used immediately after the pour. This consists of igniting a quantity of magnesium compound upon the exposed upper surface of the molten metal. This is done as another means of regulating the rate at which the casting cools. After cooling, the casting is removed from the mold. This removal, or "Knockout" process destroys the mold. In normal production,

approximately eleven castings per day are produced by this method at ACD.

Throughout the entire process, all conditions which could conceivably effect the resulting casting are controlled in minute detail. From the temperature and humidity of the wax room where the pattern is made, to the curing time and temperature of the mold, to the grit size and air pressure of the sand blaster used for knockout, all parameters are carefully scrutinized. The most vital parameters are those involving the pour itself: master heat temperature, mold temperature, pouring rate, amount of hot top material, even the type and thickness of the material the mold is set upon after the pour.

This intensive control is necessary not merely to insure uniform quality in the product, but to achieve the proper grain structure in the metal of the casting itself. Achievement of this is vital to the success of the cast monoform turbine wheel because the grain structure determines the ability of the wheel to withstand the stresses placed upon it during operation. For example, it is important that no long, columnar grains appear in the areas where the blades intersect the hub. Grain boundaries are the weakest points in a metal and are likely starting places for cracks. Extremely fine grains, resembling salt and pepper in appearance, are

low in ductility, and are not allowed in any area of the casting except in those areas which are ultimately removed by finish machining. Such grains are likely to appear along the edges of the blades, where cooling is rapid. A satisfactory grain size on the blade is one approximately equi-axial and of 1/8 to 3/16 inch in diameter. In the hub, a uniform pattern of larger grains, approximately one inch by one-half inch, is desired because of the greater rupture strength of such a pattern. As a general rule, small grains result from cold pouring temperatures and rapid cooling, and large, columnar grains, from hotter pours and slower cooling.

It becomes apparent from this that the exact temperatures, pouring rates, cooling rates, mold insulation, etc., are critical to the success of the finished product. These values can be determined only by the costly process of trial and error, utilizing the experience and judgment of the metallurgists and foundry operators involved. They are therefore considered proprietary information, and, as such, are closely guarded. (This may, in part, explain the recalcitrance of the previously-mentioned foundry.) At ACD, the process required four months and fifty trial pours before the winning combination was developed which would produce good castings consistently.

III.2 The Testing Process

The elaborate degree of control exercised during the casting process is continued into the testing procedures carried out upon the castings prior to their acceptance as production items. These procedures are rigidly defined by process specifications agreed to in contract between AiResearch and the supplier, and are performed by the supplier in the following manner.

Initially, 100% of the castings are subjected to nondestructive testing. First, two test bars are machined from the test ring, the extra material surrounding the wheel shaft in the raw casting (see Figure 3.1). One bar (#6) is then subjected to tensile testing. The second bar (#7) is tested only if the first fails to meet the specified minimum criteria. If both bars fail, the casting is rejected.

After removal of the test ring, the casting is radiographically inspected for internal imperfections, then macroetched to provide definition of grain size. Finally, all castings are coated with fluorescent penetrant and inspected for cracks and hot tears.

Pending the compilation of sufficient data, a statistical sampling method agreed upon by AiResearch and the supplier may replace the 100% testing method. Any subsequent change in the casting process, however,

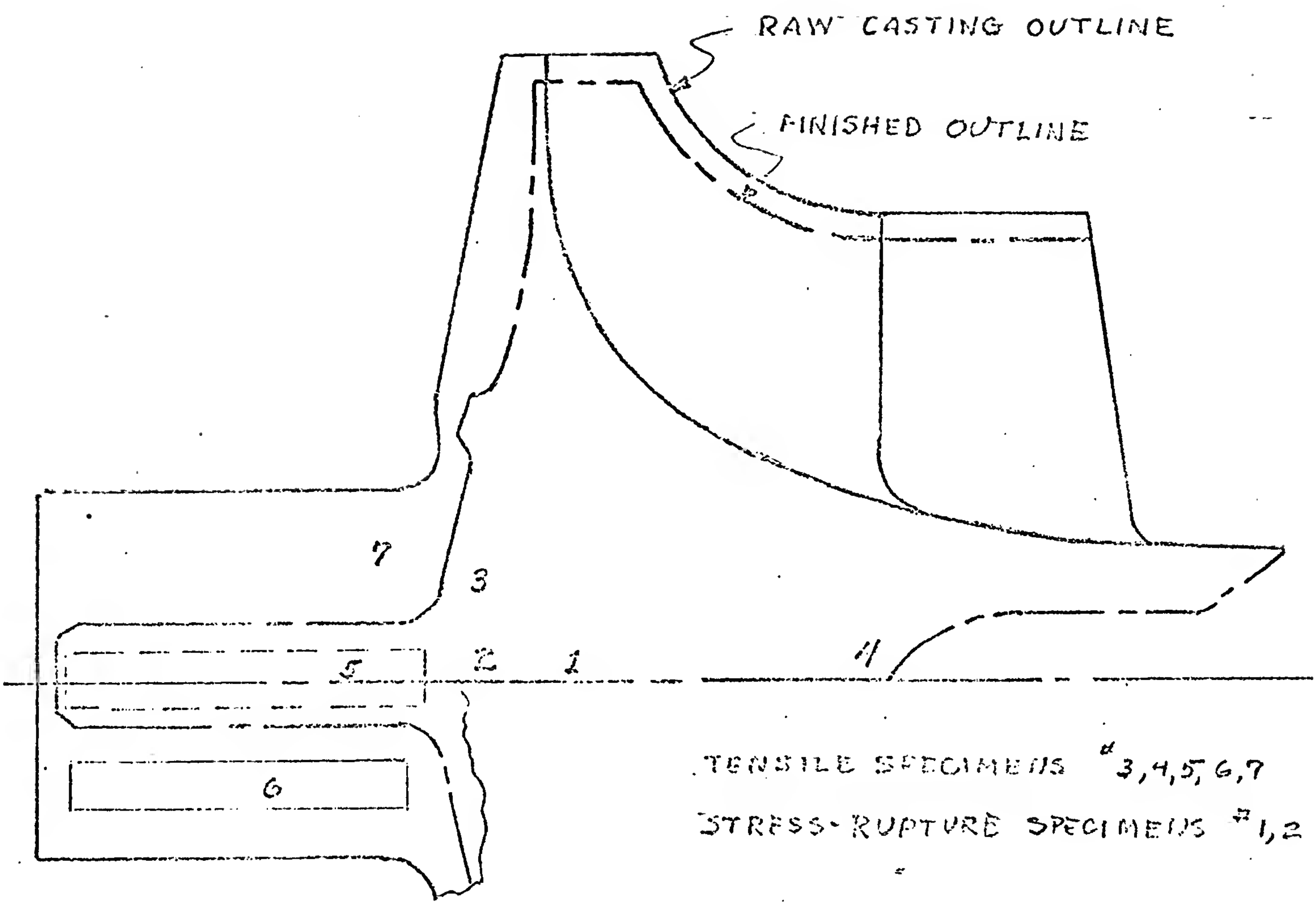

Fig. 3.1 Specimen Locations

necessitates reversion to the 100% inspection method which continues again until sufficient data for sampling are accumulated.

From each daily production lot, one casting is destructively tested. The average daily lot at ACD is

about eleven castings. Hence, the extreme emphasis placed upon quality control and assurance requires the initial sacrifice of almost ten percent of the production. The expense of such stringent standards becomes evident, even though the use of castings with minor disqualifying defects is permitted for this testing.

The destructive testing is carried out by first macroetching for grain size determination and fluorescent penetrant inspection for external cracks and hot tears. The casting is then sectioned axially in such a manner as to cut both a blade and the hub. One-half of this casting is sent to AiResearch, the other half is tested by the supplier. The sectioned area is again macroetched for grain definition and fluorescent penetrant inspected. Then the stress-rupture and tensile test specimens are machined from the areas indicated in Figure 4.1 and subjected to testing.

Prior to the production casting, each master heat, the previously refined metal of a single furnace charge, must be individually qualified. To do this, three sample castings are poured from each master heat. Two of these castings are destructively tested, and the third, only if one of the first two fail. If two castings fail, the master heat is rejected. If the first two castings pass, the third is shipped as a production wheel.

IV. A FAILURE ANALYSIS

IV.1 The Failure

An interesting facet of the development of the monoform turbine wheel was the failure during acceptance testing in late 1969, of a wheel supplied by one of the two independent foundries who, in addition to the AiResearch Casting Division (ACD), were producing these wheels. This particular wheel burst into two nearly equal parts, revealing a thumbnail sized metallurgical discontinuity in that area of the hub which is subject to the greatest stress during operation.

This failure was studied in detail by AiResearch engineers.[2] Their investigations, which included numerous attempts to duplicate the defect in the failed wheel, concluded that the defect was most probably caused by the introduction into the pour material of flake-shaped particles of contaminant. Since the interface of the defect was high in aluminum content, it was concluded that flakes of metal, remaining in the alumina (Al_2O_3) crucible from a previous pour, had become detached and had entered the succeeding pour. These flakes carried with them a coating of aluminum oxide which caused the formation of the defect.

At this point, the foundry involved decided that rather than accept the conclusions and recommendations of the AiResearch engineers, they would terminate production and forfeit a potentially lucrative contract. This decision, though incomprehensible to a detached observer, highlights the jealousy with which commercial foundries protect the details of their operations.

IV.2 Fracture Toughness Calculations

In light of the opportunity provided by this failure data, it was decided to calculate the fracture toughness of the failed turbine wheel. According to Kenny and Campbell,[1] fracture toughness is a constant expressing the resistance of a metal to crack propagation and is dependent upon material and geometry.

Figure 4.1 illustrates the concept of fracture toughness. G is defined as the strain energy release rate, the measure of energy per unit area absorbed during the infinitesimal growth of a crack.

$$G = \frac{1}{2} P^2 \left(\frac{dC}{dA}\right)$$

where P is the applied load, C is the compliance of the specimen, and A is the crack half-length. If unit thickness is assumed, A may then be considered to be the area of the crack projected on the longitudinal axis of the crack.

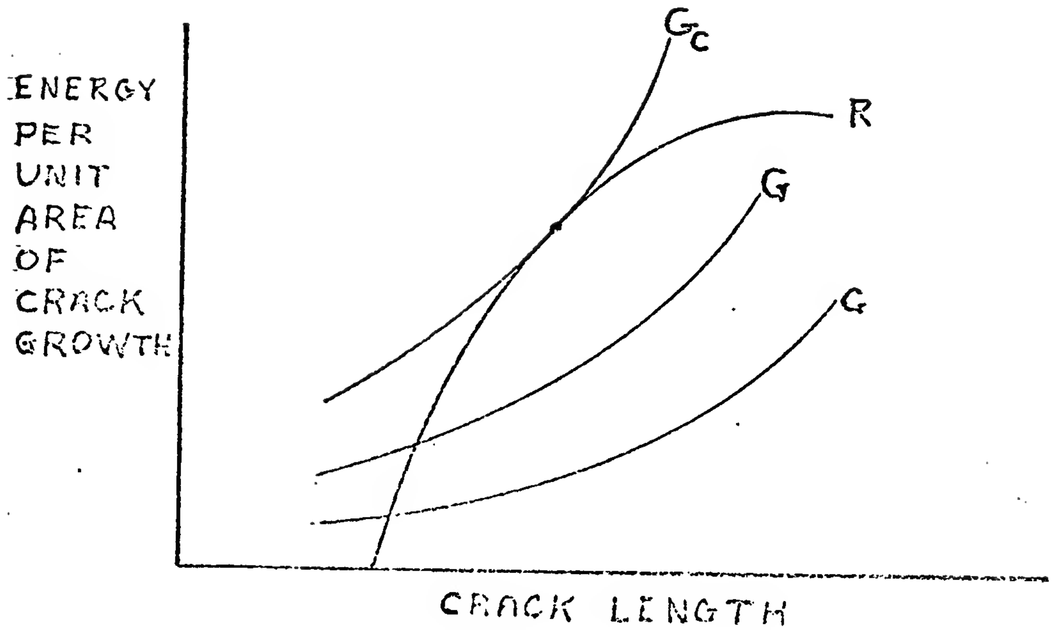

Fig. 4.1 Strain Energy vs. Crack Length

R is the resistance of the material to crack growth.

$$R = \frac{dQ}{dA}$$

where Q is the energy absorbed in creating the crack. From the figure, crack growth begins at the point where the G curve intersects the R curve. As G increases with increasing load, the two curves become tangent at point G_C, which represents the fracture toughness of the material, the critical energy release rate. As stress increases past this level, rapid crack growth takes

place, and the energy difference, G minus R, appears as kinetic energy.

Since we are concerned with a two-dimensional defect in this case, we borrow upon Tiffany and Masters[7] for the equation for plane-strain fracture toughness, K.

$$K = (1.1) \quad \pi \quad \sigma \quad A_{cr}/Q_{cr}$$

where σ is gross stress, A_{cr} is the minor semi-axis of the flaw, and Q is a flaw shape parameter, dependent, in part, upon the ratio of the gross stress to the yield stress of the material. This equation assumes an elliptical flaw shape. Also the yield stress for INCONEL 713C (75,000 psi) was used in the absence of a figure for 713 LC. The gross stress value was taken from that part of Figure 3.1 corresponding to the actual location of the flaw and 45,000 psi was used. From photographs,[2] the value of A_{cr} = .218 was determined. All this yielded a value for Q_{cr} which resulted in the following computation

$$K = (1.1)(\pi) (4.5 \times 10^4) (\frac{.218}{1.7})$$

$$K = (1.1) (1.77) (4.5 \times 10^4) (.358)$$

$$K = 31,400 \text{ psi} \sqrt{\text{in.}}$$

This figure seems reasonable in light of known values for similar materials.

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